17

Neutron Coincidence Instruments and Applications

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17.1 NEUTRON COINCIDENCE SYSTEM DESIGN PRINCIPLES

Neutron coincidence counting has been used extensively during the past few years for the nondestructive assay of nuclear material. The usefulness of the technique is due primarily to the good penetrability of fast neutrons and the uniqueness of time-correlated neutrons to the fission process and thus the nuclear material content.

In considering the design of a neutron coincidence system, the primary variables that should be considered are: (1) the type of neutron detector, (2) the moderator and shielding materials, and (3) the mass range and sample characteristics. In general, neutron coincidence counters need higher detection efficiency than total neutron counting systems because of the requirement to count at least two neutrons. This requirement makes the coincidence counting rate proportional to the square of the detector efficiency. The high efficiency is usually accomplished by good geometric coupling between the sample and the detector (for example, a 4π or well counter) and by the use of efficient thermal-neutron detectors.

Most of the neutron coincidence counters in current use contain ^3He gas tubes because of their high efficiency, reliability, ruggedness, and gamma insensitivity. Tubes containing BF_3 gas are sometimes used to reduce costs or to operate in higher gamma-ray fields; however, their efficiency is about a factor of 2 less than that of ^3He tubes. The main disadvantage of ^3He and BF_3 gas tubes for coincidence applications is that the neutrons have to slow down to thermal energy via scattering collisions before they are detected in the tubes and this slowing-down process causes a rather large die-away time (τ) in the detector. As a result, the coincidence gate time (G) in the electronics must be set at a relatively large value (10 to 100 μs) to detect the time-correlated coincidence neutrons. Ultimately the large gate length increases the statistical error for high-counting-rate applications.

Computer calculations employing Monte Carlo codes for neutron transport have been used to optimize the design of ^3He neutron coincidence detector systems. The following parameters are important in the design: (1) total neutron efficiency for spontaneous fission neutrons, (2) sensitivity to sample matrix materials, (3) neutron die-away time in the detector moderator material, and (4) weight and cost of the system. Neutron coincidence counters have been applied to the assay of a wide range of plutonium masses and container sizes, making it necessary to emphasize different parameters to achieve specified detector characteristics. Examples of the optimization of thermal-neutron counter designs by Monte Carlo calculation are given in Chapter 14.

Several assay systems based on coincidence counting have used fast-neutron recoil detectors to avoid the die-away-time problem associated with thermal counters. Examples of these detectors are liquid and plastic scintillators and ^{4}He gas recoil counters. The scintillators are sensitive to gamma-ray backgrounds and the ^{4}He tubes are relatively inefficient. Examples of coincidence systems based on fast plastic scintillators are the Random Driver, Isotopic Source Assay System, Isotopic Source Assay Fissile, and early models of fuel-pin scanners; all have been documented in previous publications (Refs. 1 through 3).

The remainder of this chapter focuses on thermal-neutron coincidence systems because they dominate the practical applications. Many of these systems have been developed to the stage where commercial equipment is now being used in nuclear fabrication facilities. Recently, inspectors have been using portable equipment to verify operator declaration of nuclear fuel content.

Because of the large range of applications, it has been necessary to develop different assay systems to accommodate difficult types of samples. In contrast to the procedure used in chemical analysis, where the sample is modified to "fit" the instrument, in nondestructive assay the instrument is modified to fit the sample. The following sections describe the instruments, principles of operation, and applications. All of the instruments described are based on the method of neutron coincidence counting using time-correlation electronic circuitry.

17.2 PASSIVE NEUTRON COINCIDENCE SYSTEMS

Neutron assay instrumentation has been standardized by using the neutron coincidence technique as a common basis for a wide range of instruments and applications. The shift-register electronics (Ref. 4) originally developed for the High-Level Neutron Coincidence Counter (HLNCC)(Ref. 5) has been adapted to both passive- and active-assay instrumentation for field verification of bulk plutonium, inventory samples, pellets, powders, nitrates, high-enriched uranium, and materials-testing-reactor, light-water-reactor, and mixed-oxide fuel assemblies. This family of instruments all use the standard shift-register electronics package. The "family tree" in Figure 17.1 shows the relationship between the standard electronics (the trunk), the assay systems (the branches), and the many different applications. The detectors for all of the assay systems are ^{3}He tubes matched to provide the same gain at the same high-voltage settings. Thus, the standard electronics package can be directly substituted between the assay systems with no change in connectors or parameters. Because the electronic components dominate the maintenance work, the total amount of maintenance effort is greatly reduced by this standardization. Operator training is also simplified because an operator trained to use the HLNCC becomes at ease with other systems after only a few minutes of orientation.

Individual instruments that are based on the standard neutron coincidence electronics include

(1) the 55-gal drum counter for scrap barrels;
(2) the HLNCC for bulk plutonium assay;

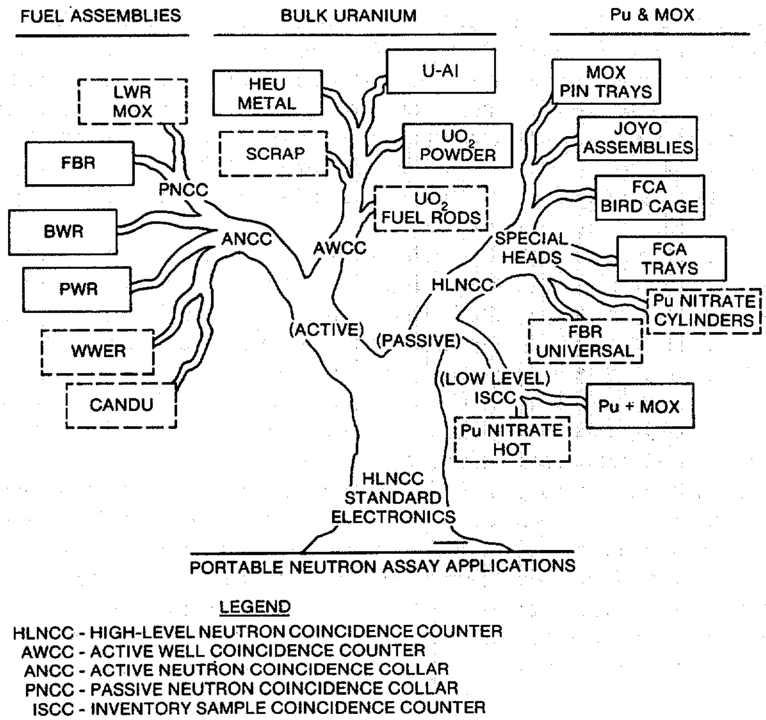

***Fig. 17.1** "Family-tree" diagram of active and passive neutron coincidence systems and applications based on the standard shift-register electronics package developed for the HLNCC.*

(3) special purpose coincidence heads for fast-critical-assembly (FCA) plates and trays, fast-breeder-reactor (FBR) subassemblies, mixed-oxide (MOX) pin trays, and plutonium nitrate bottles;
(4) the Inventory Sample Coincidence Counter (ISCC) for small samples of plutonium nitrate, pellets, and PuO_2 powders;
(5) the plutonium nitrate solution counter for in-line applications; and
(6) the universal FBR subassembly counter.

These and other passive instruments and applications are described in Sections 17.2.1 through 17.2.8.

17.2.1 The 55-Gallon Barrel Counter

An early application of passive neutron coincidence counting to plutonium measurement was the 55-gal barrel counter (Ref. 6). This system was designed to measure compacted scrap and waste in 55-gal barrels or cartons. The material could not be measured by conventional chemical techniques because it was too heterogeneous to sample.

The barrel counter shown in Figure 17.2 contains BF_3 gas tubes imbedded in a polyethylene matrix. The sides of the counter consist of a 10-cm-thick annulus of polyethylene containing thirty-six 5-cm-diam BF_3 detectors; the top and bottom of the counter consist of 10-cm-thick slabs of polyethylene, each containing nine 5-cm-diam BF_3 detectors. The annulus separates into two parts to allow introduction of a 55-gal barrel. The top and sides of the counter are surrounded by a 30-cm-thick water shield. Figure 17.2 shows a general view of the 4π barrel counter in its "open" (separated) configuration, with a 55-gal barrel inserted.

Initially the counter was operated without a cadmium sleeve on the inside of the polyethylene annulus. This configuration kept the neutron counting efficiency as high as possible and resulted in a long neutron lifetime (measured to be 125 μs). The configuration is useful for low-level counting of less than a few grams of plutonium in a barrel. The single-neutron counting efficiency was measured to be 12%, and the coincidence efficiency was measured to be 1.5%. The lifetime of 125 μs decreased to ~50 μs when a cadmium layer was inserted inside the polyethylene annulus and, as expected, the single-neutron and coincidence counting efficiencies also decreased.

It was found that neutrons generated by cosmic rays produce a considerable coincidence background in the counter. At Los Alamos (elevation ~7500 ft), this background amounts to 0.250 ± 0.002 coincidence counts/s—the same rate as from a 0.2-g sample of plutonium (20% ^{240}Pu). This coincidence background limits the sensitivity of the counter to about 0.25 g of plutonium unless a multiplicity measurement is made to correct for cosmic-ray events. Near sea level, where most commercial plutonium processing facilities are located, the cosmic-ray coincidence background will be lower by

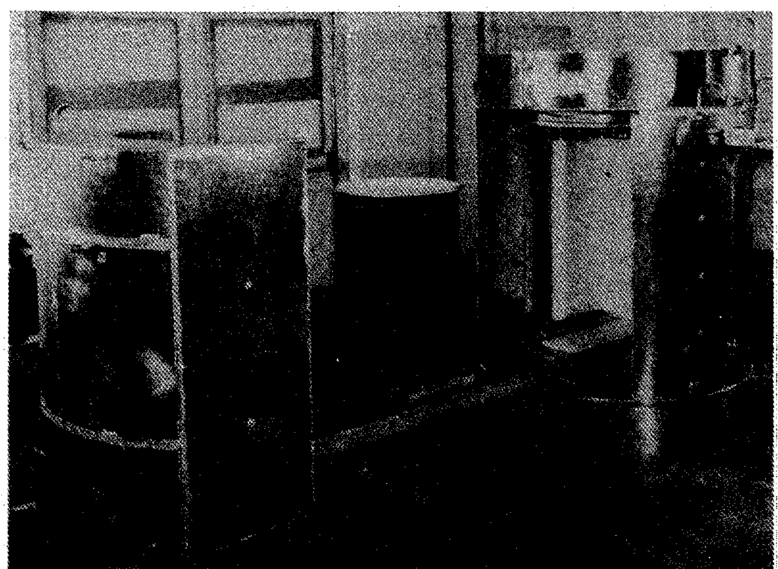

Fig. 17.2 Passive coincidence counter for 55-gal barrels.

roughly a factor of 2. The background rate can also depend somewhat on the mass and composition of the waste container. For example, when six lead bricks (77 kg) were placed in the barrel counter to measure the production of neutrons by cosmic rays in high-Z materials, the observed coincidence counting rate (above background) was 0.91 ± 0.02 counts/s, which is equivalent to about 0.7 g of plutonium (20% ^{240}Pu).

For the assay of plutonium-bearing waste, passive coincidence counting is more accurate than total neutron counting because it is not sensitive to (α,n) reactions in the matrix. However, the detection sensitivity may be less, depending on the chemical form of the material and the background coincidence rate.

17.2.2 The High-Level Neutron Coincidence Counter (HLNCC)

In 1975, work was initiated at Los Alamos to design a portable neutron coincidence counter that could measure cans containing up to 2500 g of PuO_2. The counter was to be modular so that its configuration could be modified to accommodate different geometries such as plates and pins. The design effort led to the hexagonal model shown in Figure 17.3. The intermediate layer of cadmium shown in the figure was added to reduce efficiency, matrix sensitivity, and die-away time for the counter.

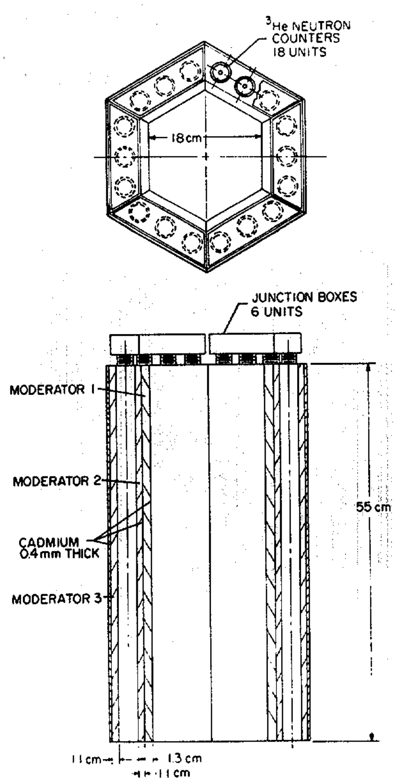

Fig. 17.3 Portable High-Level Neutron Coincidence Counter (HLNCC) for the assay of high-mass plutonium samples.

The HLNCC contains six banks of detectors, each bank containing three ^3He tubes embedded in a polyethylene matrix. The 25-mm-diam tubes have an active length of 508 mm and are filled to a pressure of 4 atm. The system has an efficiency of $\sim 12\%$ and a neutron die-away time of 32 μs (Ref. 5).

When work was initiated on the HLNCC, the maximum totals count rate that could be processed by coincidence electronics was typically 20 to 30 kHz. For this reason parallel development of a high-speed, portable shift-register electronics package was undertaken. The electronics package (Figure 17.4) contains six channels of electronics, the shift register (see Chapter 16), and a microprocessor to read out the data to a Hewlett Packard HP-97 programmable calculator or other computer. Operation of the system is very simple because of the interface between the shift register and the programmable calculator. The operator needs only to load the sample and press the start button. The data collection, reduction, error analysis, calibration, and readout are performed by the calculator.

During the past 5 years, the HLNCC has been used for a large variety of samples, including bulk PuO_2 powder, mixed-oxide powder, pellets, and pins, and FCA coupons and trays. The maximum design mass of 2.5 kg of plutonium has been extended by over a factor of 2, and the totals counting rate has been pushed up above 300,000 counts/s. At this count rate, there is a large deadtime correction of 3 to 4 for the coincidence rate and the results can only be used relative to a calibration curve with similar counting rates. The standard HLNCC detector and electronics are commercially available and are in use by both plant operators and inspectors.

Recent improvements in the HLNCC detector and electronics are described in the following section.

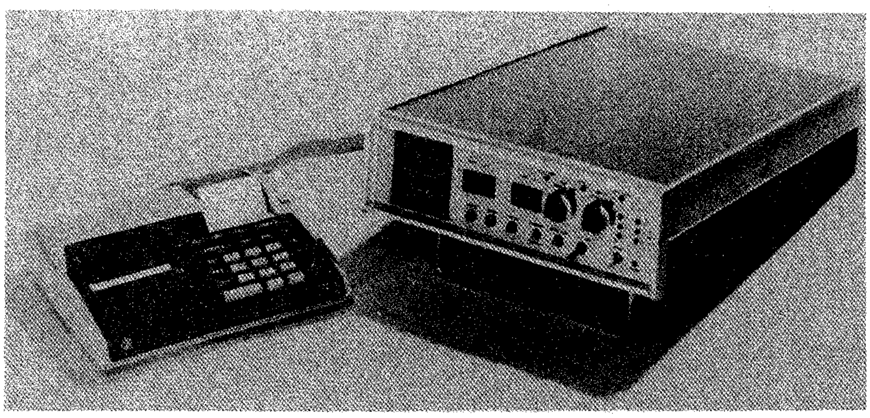

Fig. 17.4 Standard HLNCC shift-register electronics and HP-97 programmable calculator. This unit supplies the requirements for all of the assay systems shown in Figure 17.1.

17.2.3 The Upgraded High-Level Neutron Coincidence Counter (HLNCC-II)

A new upgraded version of the HLNCC has been designed and fabricated. The detector still contains 18 ^{3}He tubes, but in a cylindrical polyethylene body. Faster amplifiers have been incorporated into the electronics, and the detector body has an improved design. The vertical extent of the uniform efficiency counting zone is three times longer than that of the original unit without an increase in size or weight. Figure 17.5 is a cross-section view of the HLNCC-II, and Figure 17.6 is a photograph of the complete system.

A primary design goal for the HLNCC-II was to obtain a uniform or flat counting response profile over the height of the sample cavity while still maintaining a portable system. This was achieved by placing rings of polyethylene as "shims" at the top and bottom of the detector to compensate for leakage of neutrons from the ends. In addition to these outside rings, the interior end plugs were designed to increase the counting efficiency at each end. The end plugs were constructed of polyethylene with aluminum cores to give a better response than plugs made of either material alone would give. Also, the sample cavity has a cadmium liner to prevent thermal neutrons from reflecting back into the sample and inducing additional fissions. Because the cadmium liner does not extend into the region of the end plugs, the polyethylene in the walls of the end plugs becomes an integral part of the moderator material for the ^{3}He tubes.

The totals and coincidence response profiles of the new counter were measured by moving a ^{252}Cf source along the axis of the sample cavity. The normalized response profiles are shown in Figure 17.7, where the dashed curves refer to the original HLNCC. The improvement in response is apparent. Table 17-1 compares some of the key features of the HLNCC and the upgraded HLNCC-II.

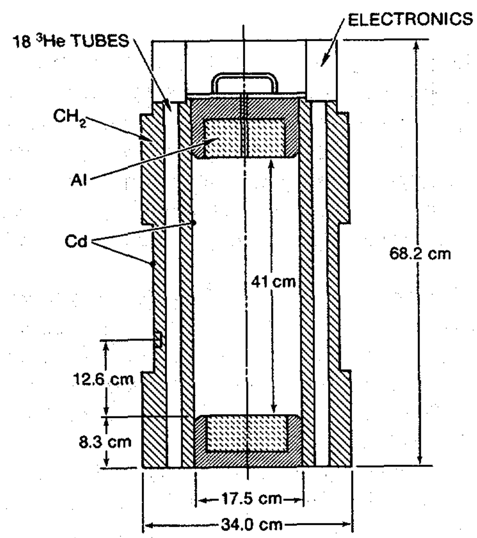

Fig. 17.5 *Cross-section view of the upgraded High-Level Neutron Coincidence Counter (HLNCC-II).*

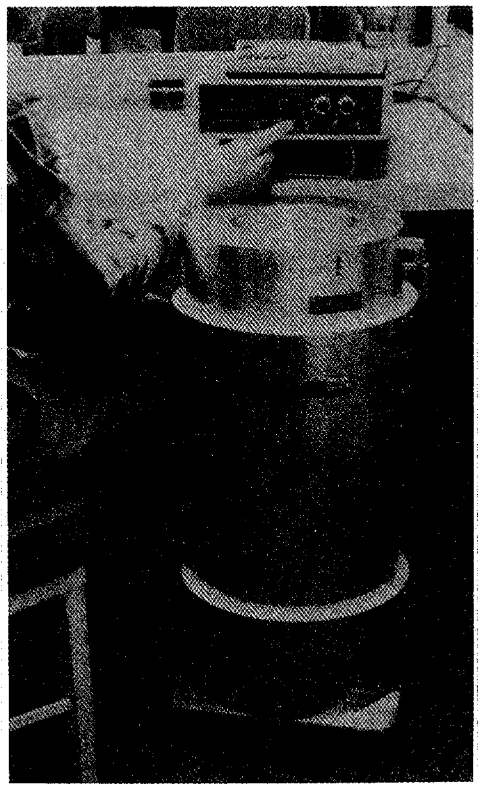

Fig. 17.6 View of the HLNCC-II showing the six indicator lights on the electronics junction box at the top of the unit and the shift-register electronics package on the table top.

The new counting electronics package developed in parallel with the HLNCC-II is based on the AMPTEK A-111 hybrid charge-sensitive preamplifier/discriminator (Ref. 7). Pulses resulting from neutron events are discriminated on the basis of pulse height from noise and gamma-ray events at the output of the preamplifier. This approach eliminates the need for additional pulse-shaping circuitry and allows a maximum counting rate of about 1300 kHz, about four times higher than previously attainable. The electronic deadtime is also a factor of 4 lower than that of the previous system (see Section 16.6.5).

The new electronics package is capable of measuring samples of significantly larger mass, usually limited only by criticality considerations. The small preamplifier/discriminator circuit is placed directly next to the base of the ^{3}He tubes inside a sealed box to enhance the signal-to-noise ratio. Under laboratory conditions, the totals counting stability was measured to be 0.002% over a 2-week counting period. This is the best stability ever observed with nondestructive assay systems.

The HLNCC-II and its new electronics have been used to assay PuO_2, PuF_4, mixed oxide, and other plutonium compounds. An example of the response of the system for PuO_2 both with and without multiplication corrections is shown in Figure 17.8. The

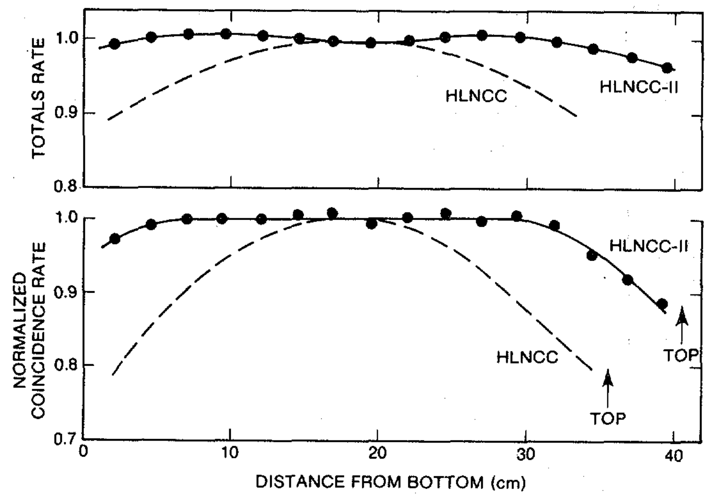

Fig. 17.7 *Normalized response profiles for total and coincident neutron counting for the HLNCC (dashed lines) and the upgraded version HLNCC-II (solid lines), showing a three-times-longer flat response profile for the HLNCC-II.*

Table 17-1. Detector parameter comparison for the HLNCC and the HLNCC-II

Item	HLNCC	HLNCC-II
Cavity diameter	17.5 cm	17.5 cm
Cavity height	35.0 cm	41.0 cm
Outside diameter	32-36 cm	34.0 cm
System weight	48 kg	43 kg
^{3}He tubes:		
(a) Number	18	18
(b) Active length	50.8 cm	50.8 cm
(c) Diameter	2.5 cm	2.5 cm
(d) Gas fill	4 atm	4 atm
(e) Gas quench	Ar + CH_4	Ar + CH_4
Efficiency	12%	17.5%
Die-away time	33 μs	43 μs
Cadmium liner	fixed	removable
Flat counting zone:		
(Coincidence, 2% from max.)	11.0 cm	30.5 cm
(Totals, 1% from max.)	10.5 cm	33.5 cm

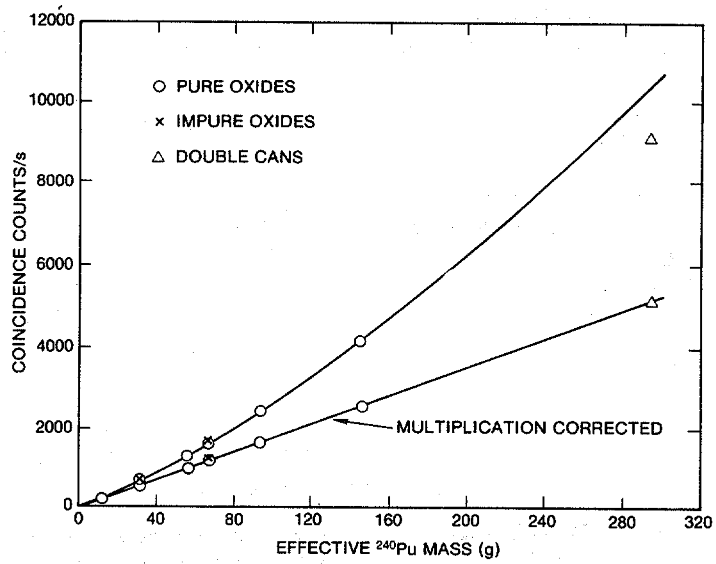

***Fig. 17.8** Coincidence response of the HLNCC-II with the new, faster electronics for a variety of large PuO_2 samples, both with and without multiplication correction.*

highest mass point, at about 300 g ^{240}Pu-effective, corresponds to two cans of PuO_2 stacked on top of each other. The air gap between the two plutonium masses reduces the geometric coupling compared to that of a single can with the same total mass. This reduction in coupling results in less neutron multiplication and causes the double-can data point to lie below the calibration curve. After the multiplication is corrected for, as described in Section 16.8, the double-can data point lies on the straight line defined by the single-can data.

17.2.4 Special Detector Heads for FCA Coupons

For many applications, it has been desirable to custom design the detector head to the specific application. Even though this specialization proliferates detectors, it reduces assay time, calibration effort, and the number of standards, and decreases the chance of error in the assay. This section and Sections 17.2.5 through 17.2.8 describe some of the special detector heads that have been developed from the HLNCC and that use the same electronics.

At fast critical assemblies, metallic plutonium coupons are typically found in rectangular storage drawers (5 by 5 by 40 cm), and it is desirable to verify the plutonium content without removing the coupons from the trays. The Channel Coincidence Counter (Ref. 8) shown in Figure 17.9 was designed for this purpose.

The principal feature of the detector is the 7- by 7-cm channel, which runs the full length (97 cm) of the detector. This channel is large enough to hold FCA fuel drawers and certain fuel-rod trays, but is small enough to permit high and reasonably uniform

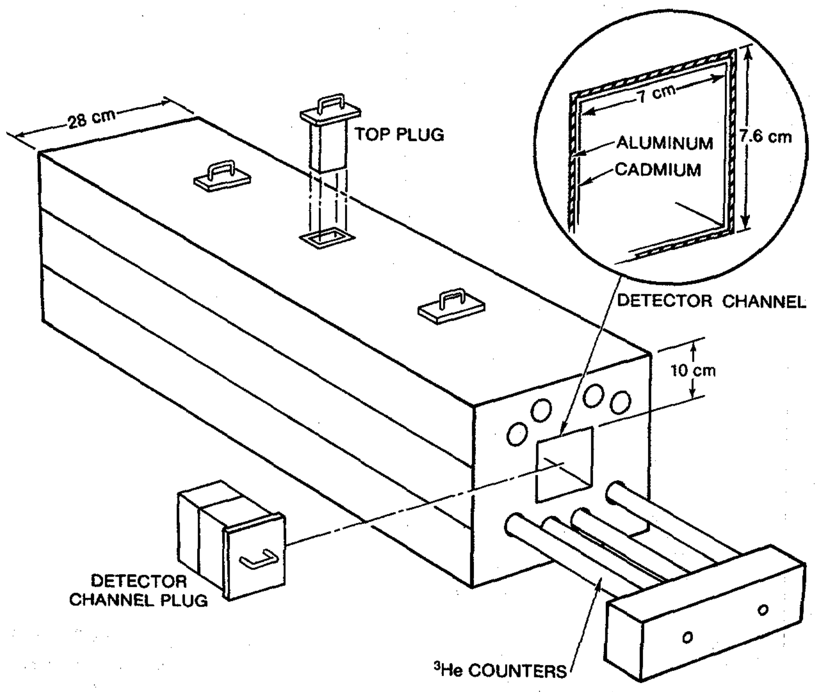

***Fig. 17.9** Isometric diagram of the Channel Coincidence Counter used for the assay of fast-critical-assembly (FCA) fuel trays and mixed-oxide fuel rods.*

coincidence counting efficiency. Three top plugs are also provided with the system. Any one of these can be removed to provide a slot for gamma-ray measurements of the sample. The center top plug is also used as a source holder for detector calibration.

A calibration curve for plutonium plates in FCA drawers is shown in Figure 17.10. The data used for the construction of this curve were acquired with zero-power plutonium-reactor (ZPPR) fuel plates arranged in single, double, and triple rows with matrix materials of iron, aluminum, carbon, and depleted uranium. An increase in the response caused by neutron multiplication is evident for the higher plutonium mass loadings. Also, the data for triple rows of plutonium plates show an increased multiplication compared to single and double rows. The standard self-multiplication correction technique (see Section 16.8) will correct for these differences. The precision for counting FCA drawers is better than 1% in 1000 s. This Channel Coincidence Counter is in routine use at a critical assembly facility (Ref. 9).

A Bird Cage Counter was designed for assaying the same plutonium metal coupons, but it was necessary to make the measurement inside of the "bird cage" used to store and transfer the coupons. The detector consists of ^{3}He tubes in a polyethylene matrix. The detector has a rectangular shape and an open interior region to set over the cylindrical storage canister. The coincidence response shows a neutron multiplication increase for the higher mass loadings. Precision and accuracy of $\sim 1\%$ can be obtained in counting times of 1000 s. This counter is in routine use at FCA facilities.

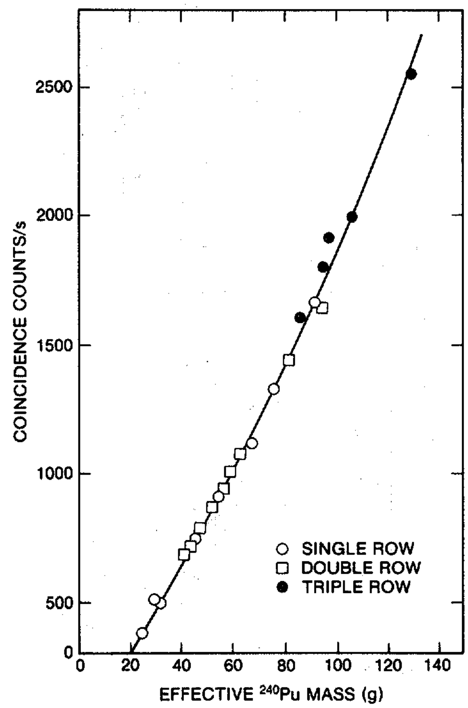

Fig. 17.10 *Calibration curve for single, double, and triple rows of plutonium plates in FCA fuel drawers.*

17.2.5 Special Detector Heads for FBR Fuel

A special neutron coincidence counter has been designed for verification of FBR fuel pins contained in storage trays (Ref. 10). The tray counter, shown in Figure 17.11, consists of a flat array of ^{3}He tubes in polyethylene slabs. A through slot in the counter provides a cavity for insertion of the stainless steel tray used by the facility operator to handle fuel pins in batches of 24. The tray can be inserted into the front of the counter and removed from the front or back as the user desires. Unlike the more desirable geometry found in cylindrical or hexagonal counters, the tray counter is flat. It is therefore necessary to match the individual detector banks to obtain a uniform spatial response. The uniform response region is ~55 cm long and 30 cm wide, corresponding to the active plutonium region of the fuel pins. The tray requires a clearance height of about 25 mm.

The detector can be used to measure a tray of FBR pins in 2 to 3 min with a sensitivity of much better than one pin. The primary advantage of the counter is that verification of a full tray of pins is possible without unloading or handling individual pins. The FBR fuel-pin tray counter is currently being used at a plutonium fuel fabrication facility.

FBR subassemblies contain large quantities of plutonium (5 to 16 kg), and the verification of this material is of high safeguards importance. Figure 17.12 is a photograph of the cylindrical coincidence counter used for the measurement of FBR fuel subassemblies. The unit consists of 12 ^{3}He tubes placed in a polyethylene annulus for

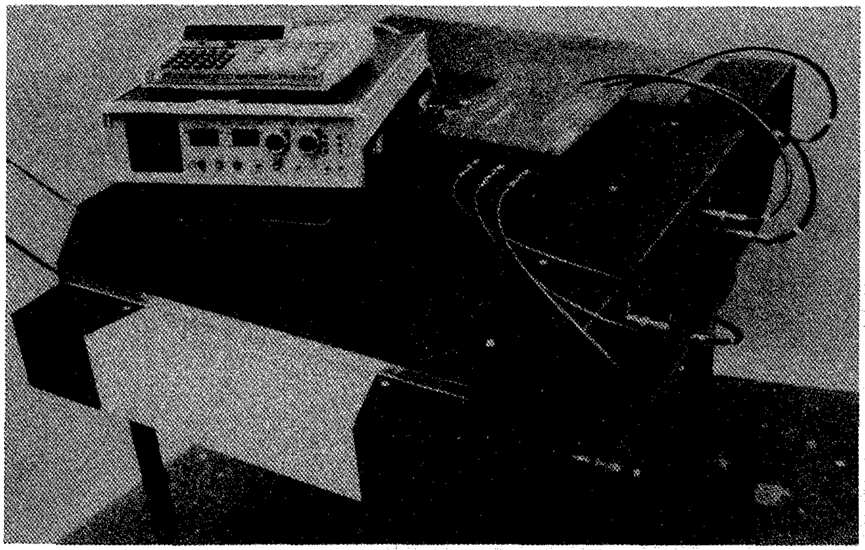

***Fig. 17.11** The fast-breeder-reactor (FBR) fuel-pin tray counter used for the verification of pin storage trays. The standard shift-register electronics package and preamplifier junction box are on top of the counter.*

neutron moderation. The active length of the detector is 1.21 m so that the entire plutonium region is contained inside the counter. The absolute efficiency of the counter is ~7%. The initial design of the counter gave a uniform response over the central 60-cm region, which is adequate for the smaller prototype FBR.

Several FBR reactors have plutonium-active regions as long as 92 cm and use subassemblies with plutonium mass loadings up to 15 kg. The 15-kg mass loading is about a factor of 3 higher than the mass that can be conveniently measured with the conventional electronics designed for the HLNCC. The need to measure entire FBR subassemblies with high mass loadings led to the development of the Universal FBR Counter (UFBR)(Ref. 11). This counter provided the first practical application of the new faster AMPTEK counting electronics (Ref. 7).

Figure 17.13 shows the UFBR detector system with the analog portion of the electronics system located at the top of the cylindrical detector. The detector is long enough to completely contain the active plutonium region of FBR subassemblies. To obtain a flat response over the 92-cm fuel length, each of the 12 ^{3}He tubes is surrounded by a layer of polyethylene and cadmium. The cadmium is removed near the ends of the detector to increase the efficiency at the ends and to compensate for the leakage of neutrons. Figure 17.14 shows the normalized totals and coincidence response as measured along the axis of the detector using a ^{252}Cf source.

In the UFBR counter, the ^{3}He tubes have an active length of 122 cm and a diameter of 2.54 cm and are filled with 4-atm gas pressure. The efficiency of the system is 7.2% and the neutron die-away time is 21.6 μs. These specifications result in a measurement precision of 0.5% (1σ) in a 1000-s counting time for typical FBR fuel subassemblies. Two

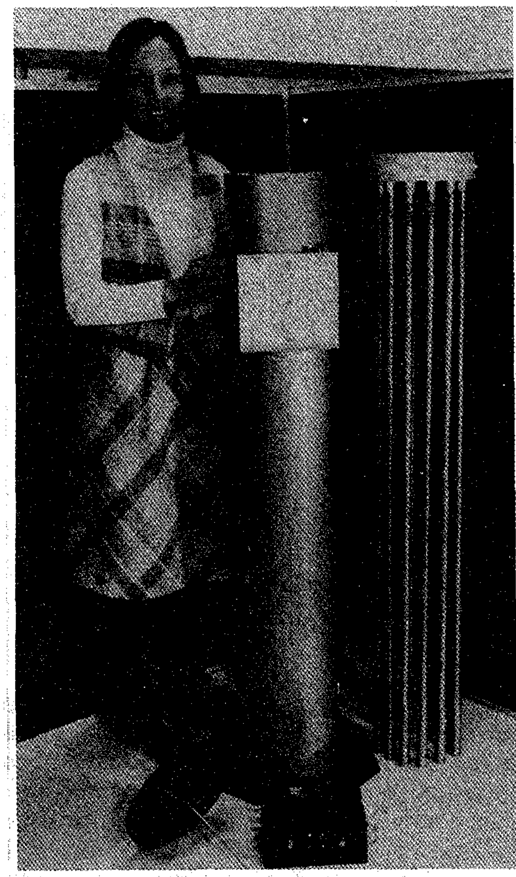

Fig. 17.12 Cylindrical coincidence counter for the verification of FBR fuel subassemblies.

of these systems are undergoing field test and evaluation for the future verification of FBR subassemblies. The initial testing and calibration of the system was performed using Fast Flux Test Facility subassemblies at the Washington Hanford Company in Richland, Washington.

17.2.6 Inventory Sample Coincidence Counter (ISCC)

Analysis of plutonium inventory samples by inspectors has been made increasingly difficult by transportation regulations. To reduce shipping requirements and to obtain more timely results, independent on-site verification capability is needed, particularly for reprocessing plants and plutonium facilities. This need has led to the development of the Inventory Sample Coincidence Counter (ISCC)(Ref. 12) for quantitative verification of the amount of plutonium in product inventory samples. The system is portable, and the samples can be assayed in the vials normally used to transfer samples to an analytical

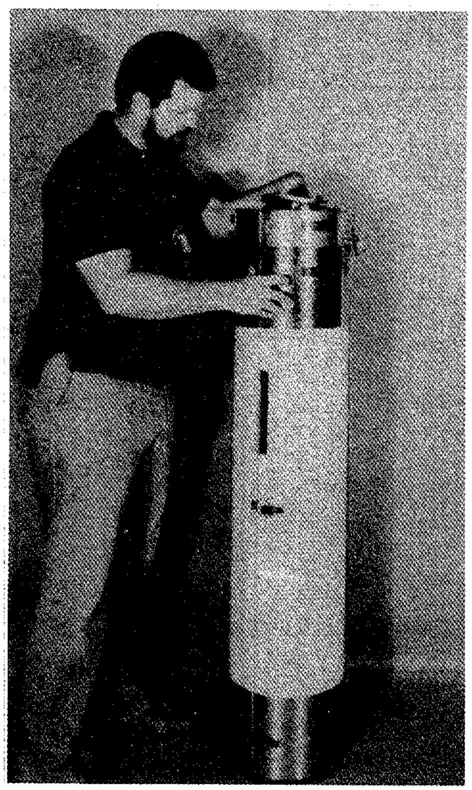

***Fig. 17.13** The Universal FBR (UFBR) Counter with the new AMPTEK electronics used for measuring FBR fuel subassemblies.*

laboratory. Pellets and powders can also be assayed. This unit uses the same electronics as the HLNCC, but it is much more efficient and is designed to operate in a much lower mass range (0.1 to 500 g Pu).

Figure 17.15 shows the ISCC detector body. The sample cavity accommodates samples that fit in the 5-cm-diam by 14-cm-tall cylindrical sample holder. The sample cavity enlarges to a diameter of 8.8 cm by removing the polyethylene cylinder. The high-density polyethylene moderator and the detector tube spacing were designed to make the system relatively insensitive to hydrogenous material in the sample matrix. The 35% efficiency of the ISCC is about three times larger than that of the HLNCC, and thus the required measurement time for small samples is about one-ninth that of the HLNCC.

Because the ISCC is physically limited to small samples, the neutron attenuation and multiplication effects are small and the calibration curves are very nearly a straight line given by the function $m = aR$, where m is the ^{240}Pu-effective mass, R is the coincidence rate, and a is the calibration constant. For solution samples such as plutonium nitrate, there is a slight amount of neutron-induced multiplication. This curvature is approximated by the power function $m = aR^b$, where b is close to unity.

The ISCC can assay individual mixed-oxide pellets or groups of several pellets. Figure 17.16 shows the counting precision (1σ) as a function of measurement time. A sample containing four typical mixed-oxide or fast-breeder-reactor fuel pellets gives a precision

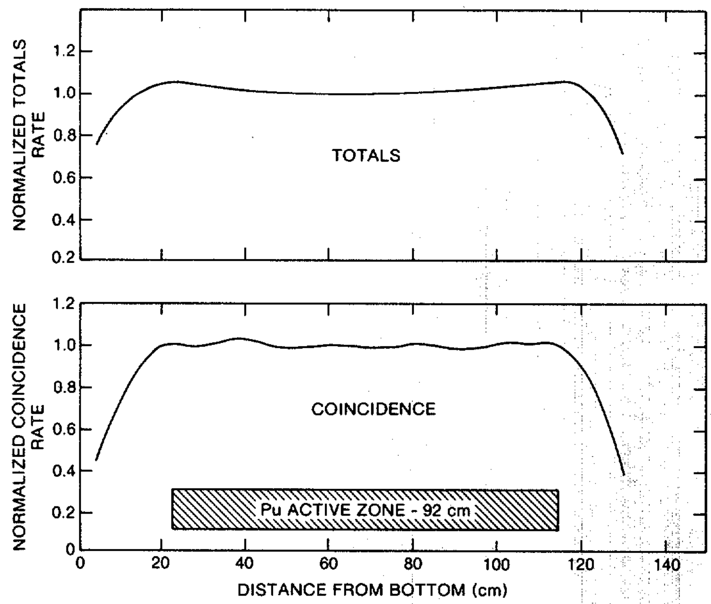

Fig. 17.14 Normalized totals and coincidence response along the axis of the UFBR counter.

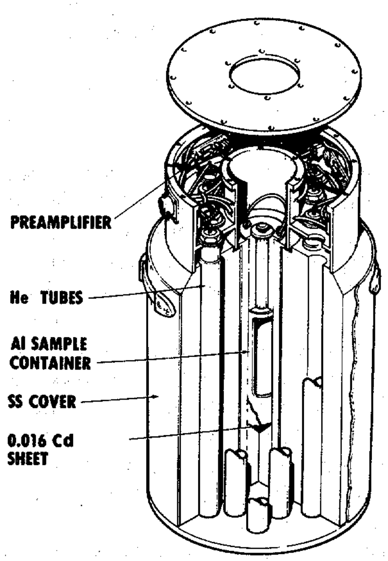

Fig. 17.15 Isometric drawing of the Inventory Sample Coincidence Counter (ISCC).

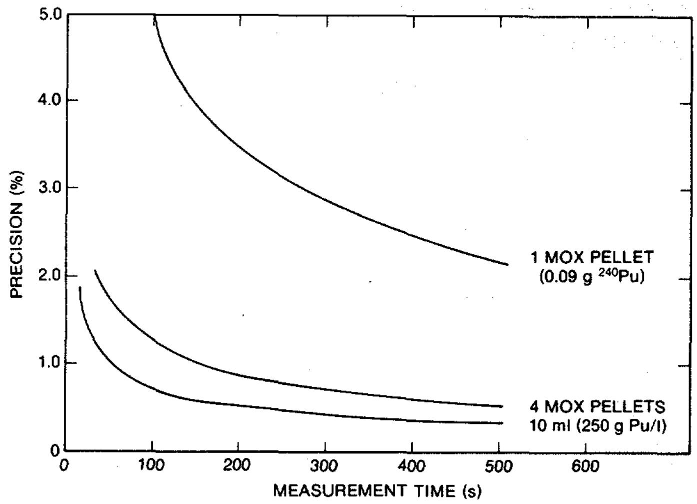

Fig. 17.16 *Assay precision as a function of measurement time for typical mixed-oxide samples in the ISCC.*

of ~1% in 200 s. A set of mixed-oxide fuel pellet standards was used to establish a calibration curve. Figure 17.17 shows the response function for the individual pellets. The percentage of plutonium in the pellets (Pu/PuO_2-UO_2) ranged from 1.4 to 21.6%. A straight line gave an excellent fit to the data. Because of the relatively small amount of material in the sample, the particular shapes or densities do not affect the measurement. Thus, samples of PuO_2 powder fall on the same calibration curve as pellets.

A set of plutonium nitrate solution standards was prepared for use in calibrating the ISCC. The solutions ranged in volume from 3 to 9 mL and the concentration varied from 150 to 350 g/L. The assay results did not depend on the volume over this range, but the solutions with larger plutonium masses gave a slightly larger (~5%) response per gram because of neutron multiplication.

Because the calibration curves are nearly linear, the requirements for physical standards are reduced. A ^{252}Cf calibration source can be used for in-field normalization of the electronics system to a previously measured calibration curve. Another approach is to establish a normalization standard at the nuclear facility. For example, two fuel pellets can be taken from the inventory and carefully measured in the ISCC. Then one pellet can undergo destructive chemical analysis and the other can be sealed and used as a long-term normalization standard. This procedure is essentially the same as that used for the ^{252}Cf source calibration, but the ^{252}Cf source calibration takes less time for the routine normalization measurement and the source can be more easily handled and transported because it contains only ~4 μCi of activity (about 10^6 times less than a plutonium standard).

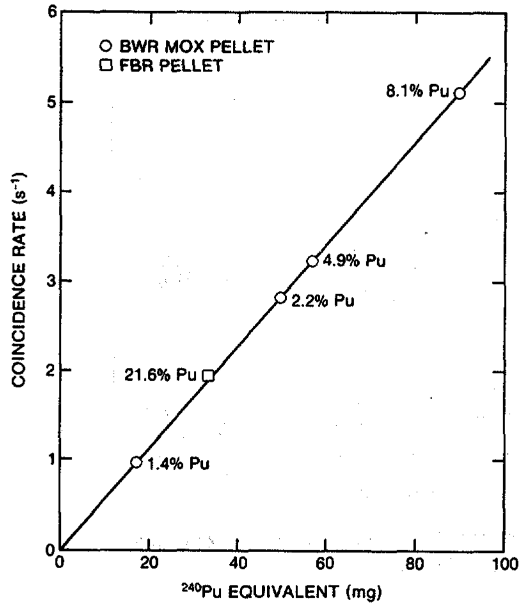

Fig. 17.17 *Coincidence response of the ISCC for mixed-oxide fuel pellets (circles).*

17.2.7 Counters for Bulk Plutonium Nitrate Solutions

In principle, the spontaneous fission of the even isotopes of plutonium can be detected as readily in solutions as in metals or oxides. The uniform density, distribution, and matrix material of the solution can in fact yield very precise and reproducible assays. In practice, however, neutron moderation and absorption within the solution can bias the assay. This section describes two neutron coincidence counters designed specifically for the assay of solution samples of 1 L or more in which such effects can be observed.

The Solution Neutron Coincidence Counter (SNCC)(Ref. 13) was developed for the assay of flowing solutions that are too bulky or contain too many fission products to assay conveniently by gamma-ray counting. Figure 17.18 illustrates the SNCC with its interior assay chamber of 1-L volume and its inlet and outlet tubes. Twenty-six ^{3}He tubes are tightly spaced in two rings around the chamber to achieve high counting efficiency. The 50-cm active-length tubes confine the sensitive detection volume to the bottle. Partial cadmium liners are used to obtain a nearly flat axial efficiency profile. Because the solution provides ~2.6 cm of moderator thickness, only 1.1 cm of additional polyethylene is used between the solution and the first ring of ^{3}He tubes to provide optimum response for plutonium solutions. With this thickness, the absolute efficiency is 33% and the die-away time is 38 μs. Including its 10-cm-thick polyethylene shield and 1-cm-thick steel shell, the SNCC is 48 cm in diameter by 82 cm long.

The SNCC was installed above an experimental glovebox in the Los Alamos Plutonium Processing Facility. Bottles of solution were transferred to the glovebox by the plant's conveyor system. The solution was then drawn up into the counter by

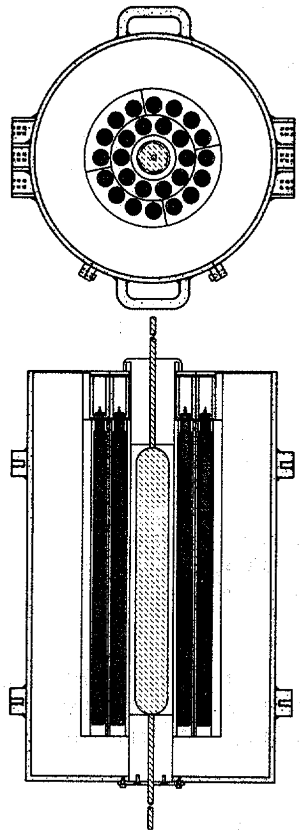

***Fig. 17.18** Top and side views of the Solution Neutron Coincidence Counter (SNCC) showing the 1-L-volume assay chamber and the inlet and outlet tubes.*

vacuum through doubly contained stainless steel tubing. The neutron counter can be assembled or disassembled without disturbing the solution transfer loop. Thus, for an actual in-plant installation, the SNCC can be assembled around an existing pipe without penetration of the plumbing.

Plutonium nitrate solutions ranging from 2 to 100 g/L of plutonium (0.2 to 12 g/L ^{240}Pu) were assayed in the SNCC. Each solution was assayed repeatedly to verify stability and reproducibility. The assay results were compared with chemical analysis of samples by coulometric titration or isotopic dilution mass spectrometry. The results plotted in Figure 17.19 show upward curvature due to self-multiplication in the solution. When corrected for this effect and fitted to a straight line, the nondestructive assay results show a 1.6% scatter relative to chemistry.

A Plutonium Nitrate Bottle Counter (PLBC)(Ref. 14) was designed for the assay of plutonium nitrate in large 10-cm-diam by 105-cm-high bottles. This detector is similar in size and shape to the FBR fuel subassembly counter shown in Figure 17.12. It is intended for use in reprocessing plants or nitrate-to-oxide conversion facilities where

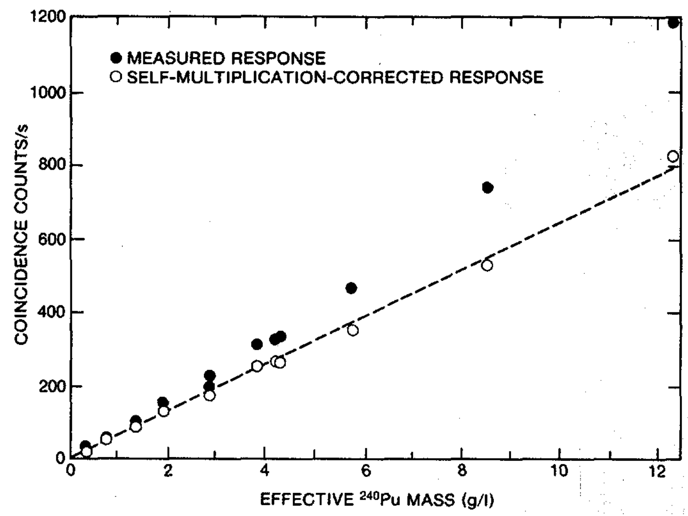

Fig. 17.19 *Assay of plutonium nitrate solutions with the SNCC. Neutron coincidence counts per second are plotted as a function of ^{240}Pu concentration, with and without self-multiplication correction.*

such large bottles are used. Initial assay results for three of these bottles are shown in Figure 17.20. The middle sample (at about 100 g/L) has more multiplication than the largest sample (about 200 g/L). Above 100 g/L the decrease in hydrogen concentration leads to a decrease in multiplication.

17.2.8 The Dual-Range Coincidence Counter (DRCC)

For many applications of neutron well coincidence counters, it is desirable to assay samples with masses in the range from less than one gram to a few kilograms of PuO_2. To achieve this wide-range capability, the Dual-Range Coincidence Counter (DRCC) (Ref. 15) was designed and fabricated. The dual-range capability is achieved by having two removable cadmium sleeves near the ^{3}He detectors. These sleeves can be inserted for low-efficiency operation with a short die-away time and removed for high-efficiency counting with a long die-away time.

The geometry of the counter is shown in Figure 17.21. The cadmium sleeves on both sides of the middle polyethylene cylinder (moderator) are removable. The detector consists of 20 ^{3}He tubes of 2.54-cm diameter filled to a pressure of 4 atm. The inner and outer polyethylene cylinders (moderators) are each 3.0 cm thick. The cadmium sleeve (1.0 mm thick) on the inside of the well stops low-energy neutrons from returning to the sample position, thereby reducing multiplication for high-mass loadings. The outer cadmium sleeve improves the effectiveness of the exterior 10-cm-thick polyethylene shield.

Thus, the counter has two modes of operation: (1) one for the low-mass range, with both removable cadmium sleeves removed for maximum efficiency, and (2) one for the

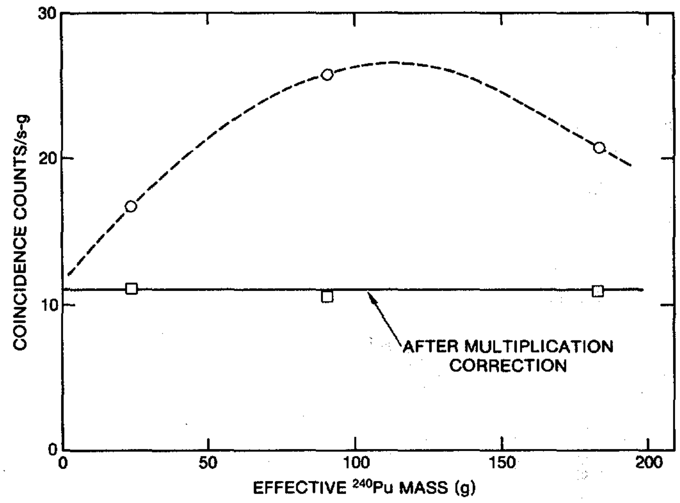

Fig. 17.20 *Assay of large plutonium nitrate cylinders with the Plutonium Nitrate Bottle Counter (PLBC). Coincidence response per gram is plotted as a function of ^{240}Pu mass, with and without self-multiplication correction.*

high-mass range, with all the cadmium sleeves in place to give a short die-away time and correspondingly short electronic gate width in the coincidence circuitry. For operational mode (1), the singles efficiency is 22% and the neutron die-away time is 52 μs. For operational mode (2), the efficiency decreases to 7% and the die-away time decreases to 16 μs.

An in-plant test and evaluation (Ref. 16) of the counter was performed at the Savannah River Plant Separations Area. A variety of incoming plutonium metal and oxide shipments were assayed with the counter. During the test period of 18 months, the dual-range counter operated with good reliability and stability. For large metal and oxide samples, assay precision based on counting statistics and reproducibility was better than 1% (1σ). Assay accuracy was 2% (1σ) for pure metal samples if a self-multiplication correction was used. Assay accuracy was 3% (1σ) for plutonium oxide if separate nonlinear calibration curves, without self-multiplication corrections, were used for each type of oxide. Assay accuracy was on the order of 10% (1σ) for impure metal samples. For a limited number of scrap samples the accuracy varied between 5 and 25% (1σ).

A dual-range counter manufactured by the National Nuclear Corp. is used by the Rockwell Hanford Facility, Richland, Washington, to rapidly verify plutonium-bearing items before shipment or after receipt (Ref. 17). Measurements on roughly 1000 items are reported in Ref. 17. The average scatter (per sample) between the book value and passive neutron assay (see Figure 17.22) is 4% (1σ) for plutonium metal. Other results are 5% (1σ) for plutonium oxide, 3% for polystyrene cubes with mixed plutonium and uranium, 27% for fuel-rod scrap, and 70% for miscellaneous scrap. Summing over each category yields a bias between book value and assay of about 1% for metal, oxide, and the polystyrene cubes, and 10% for the other scrap.

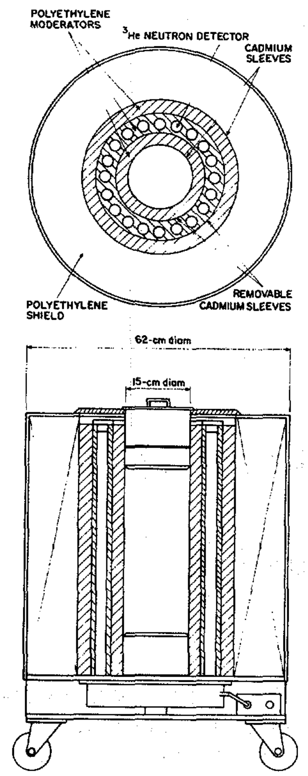

Fig. 17.21 Dual-Range Coincidence Counter (DRCC) for the assay of plutonium samples in the mass range 1 to 4000 g.

The above in-plant experience with the dual-range counter showed that neutron coincidence counting provided assay accuracies of 2 to 4% for well-characterized plutonium metal and oxide. For heterogeneous oxide and impure metal, coincidence counting did not have a clear-cut advantage over total neutron counting. This is because the self-multiplication correction was useful only for pure metal and very well characterized oxides where geometry effects were greater than (α,n)-induced multiplication effects. For other large, multiplying samples the total neutron response often provided a more accurate assay because it was less sensitive to multiplication. On the other hand, for scrap materials with low multiplication where it was necessary to discriminate against neutrons from strong (α,n) reactions or high room backgrounds, the coincidence response was more accurate. For a wide range of material categories, it is generally useful to measure both the coincidence and the total neutron response.

17.3 ACTIVE NEUTRON COINCIDENCE SYSTEMS

The passive HLNCC and the many specialized detector heads that evolved from it have been particularly useful for passive assay of plutonium. However, these instruments cannot be used for passive assay of most uranium samples because of the

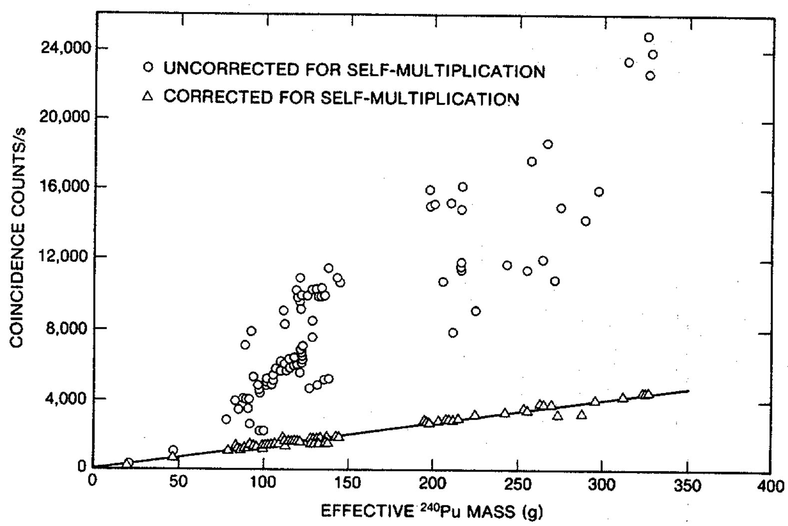

Fig. 17.22 *Assay of plutonium metal with a dual-range counter at the Rockwell Hanford Facility (Ref. 17). When corrected for self-multiplication, the assay data show a 4% (1σ) scatter relative to calorimetry and mass-spectrometry isotopics.*

extremely low spontaneous fission yields. For assay of uranium, active neutron coincidence counters have been developed that use the same electronics package, are equally portable or transportable, and use small AmLi random neutron sources for subthreshold interrogation of ^{235}U or ^{233}U. These active neutron coincidence counters can also be operated in the passive mode by removing the interrogation sources. They are described in this chapter because of their similarity to passive counters. They include

(1) the Active Well Coincidence Counter (AWCC),
(2) the Uranium Neutron Coincidence Collar (UNCC),
(3) the Passive Neutron Coincidence Collar (PNCC), and
(4) the Receipts Assay Monitor (RAM) for UF_6 cylinders.

17.3.1 The Active Well Coincidence Counter (AWCC)

Figure 17.23 illustrates the design of the AWCC (Ref. 18). The appearance is very similar to that of a passive coincidence counter except for the two small (~5 × 10^4 n/s) AmLi neutron sources mounted above and below the assay chamber. Two rings of ^{3}He tubes give high efficiency for counting coincidence events from induced fissions. The AmLi sources produce no coincident neutrons but do cause many accidental coincidences that dominate the assay error (see Section 16.7.2). Thus the polyethylene moderator and cadmium sleeves are designed for most efficient counting of the induced fission neutrons but inefficient counting of the (α,n) neutrons from the AmLi interrogation source.

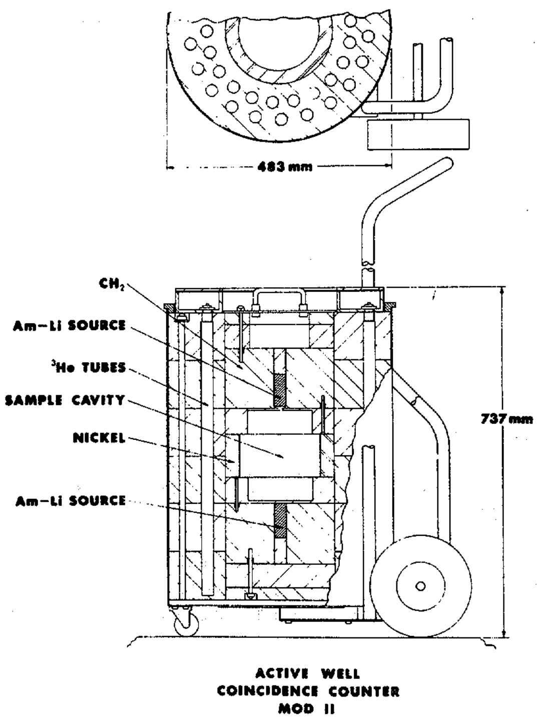

Fig. 17.23 Schematic diagram of the Active Well Coincidence Counter (AWCC) showing the ^{3}He detector locations, the neutron moderators, and the cadmium-lined sample cavity.

The nickel reflector on the interrogation cavity wall gives a more penetrating neutron irradiation and a slightly better statistical precision than would be obtained without it. With the nickel in place, the maximum sample diameter is 17 cm. For larger samples, the nickel can be removed to give a sample cavity diameter of 22 cm. The end plugs have polyethylene disks that serve as spacers; the disks can be removed to increase the sample chamber height. Removing the disks on the top and bottom plugs allows the cavity to accommodate a sample that is 35 cm tall.

A cadmium sleeve on the outside of the detector reduces the background rate from low-energy neutrons in the room. A cadmium sleeve in the detector well removes thermal neutrons from the interrogation flux and improves the shielding between the ^{3}He detectors and the AmLi source; with this cadmium sleeve in place the AWCC is said to be configured in the "fast mode." The neutron spectrum is relatively high energy, and the counter is suitable for assaying large quantities of ^{235}U. With the cadmium sleeve removed, the AWCC is in the "thermal mode." The neutron spectrum is relatively low energy and the sensitivity of the counter is greatly enhanced, but the penetrability of the interrogation neutrons is very low. In the thermal mode the counter is suitable for assaying small or low-enriched uranium samples.

Table 17-2 summarizes the performance characteristics of the AWCC for both the fast and thermal modes of operation. The absolute assay precision is nearly independent of

Table 17-2. Performance characteristics of the AWCC

Characteristic	Thermal Mode	Fast Mode
Detection efficiency		28%
Die-away time		50 μs
Range	0-100 g ^{235}U	100-20 000 g ^{235}U
Low-enrichment U_3O_8	11 counts/s-g ^{235}U	0.18 counts/s-g ^{235}U
High-enrichment metal	NA	0.08 counts/s-g ^{235}U
Absolute precision for large samples (1000 s)	0.3 g ^{235}U	18 g ^{235}U
Sensitivity limit[a] for small samples (1000 s)	1 g ^{235}U	24 g ^{235}U

[a]Defined as net coincidence signal equal to 3σ of background in 1000-s counting times.

the mass being assayed, (see Section 16.7.2). In general, the AWCC is best suited for high-mass, highly enriched uranium samples and should not be used for low- ^{235}U-mass samples except for well-defined samples in the thermal mode. The AWCC can also be used for the passive assay of plutonium by removing the AmLi sources.

In comparison with the conventional fast Random Driver (Ref. 1), the AWCC is more portable, lightweight, stable, and less subject to gamma-ray backgrounds. This last feature makes it applicable to ^{233}U-Th fuel-cycle materials, which generally have very high gamma-ray backgrounds from the decay of ^{232}U. The Random Driver has the advantage that the neutron interrogation spectrum has a higher average energy and thus gives better penetration (Ref. 19). Also, the Random Driver has a 1000-times-shorter coincidence gate length, making it possible to use higher interrogation source strengths to improve sensitivities.

The AWCC has been evaluated for several measurement problems that are of interest to inspectors. These include (1) high-enriched-uranium (93% ^{235}U) metal buttons weighing approximately 1 to 4 kg, which are input materials to fabrication facilities; (2) cans of uranium-aluminum scrap generated during manufacture of fuel elements; (3) cans of uranium-oxide powder; (4) mixtures of uranium oxide and graphite; (5) uranium-aluminum ingots and fuel pins; and (6) materials-testing-reactor (MTR) fuel elements.

Typical calibration curves are shown in Figures 17.24 and 17.25 for cases (1), (3), and (4). All the calibration curves show the effects of neutron absorption within the uranium, and Figure 17.24 also shows the opposing effect of self-multiplication within the metal.

Recent field tests (Ref. 20) with MTR fuel elements have shown that it is possible to obtain ~1% accuracy in assay times of 400 s. The advantage of the AWCC over the traditional gamma-ray assay for MTR fuel elements is that the AWCC has no problems with different plate geometries and lower ^{235}U enrichments. For applications to MTR-type fuel elements and plates, the AWCC is reconfigured as shown in Figure 17.26 (Ref. 21). The two AmLi sources are positioned in the interior of the polyethylene insert that holds the MTR elements. Figure 17.27 shows the calibration curve for typical MTR fuel plates and elements.

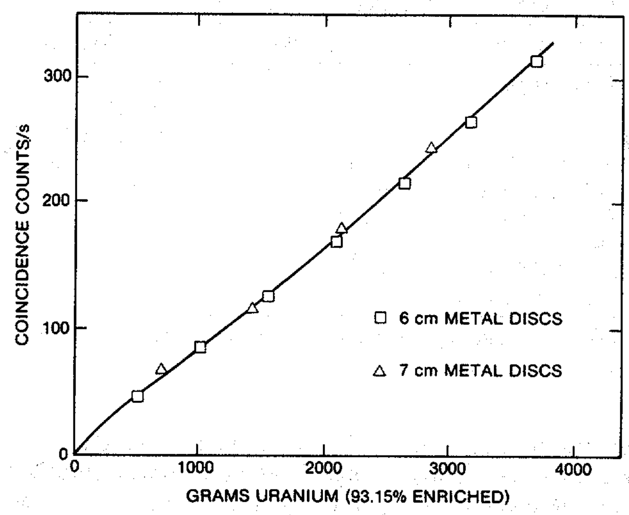

Fig. 17.24 *AWCC response as a function of uranium mass for 6- and 7-cm metal discs stacked together to obtain the total masses shown (Ref. 19).*

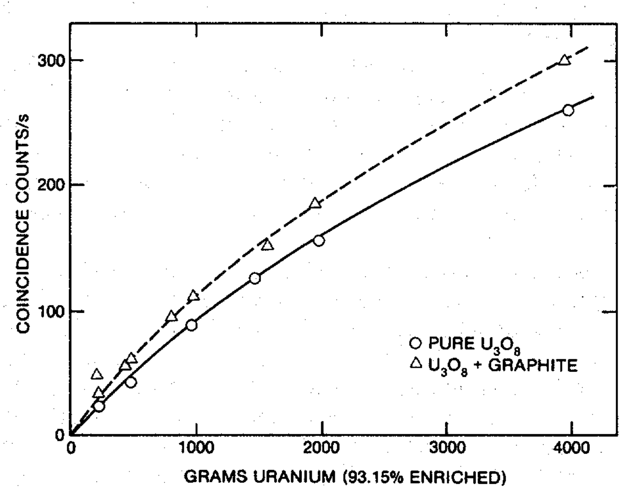

Fig 17.25 *AWCC response as a function of uranium mass for highly enriched uranium oxide powder and mixtures of uranium oxide and graphite (Ref. 19).*

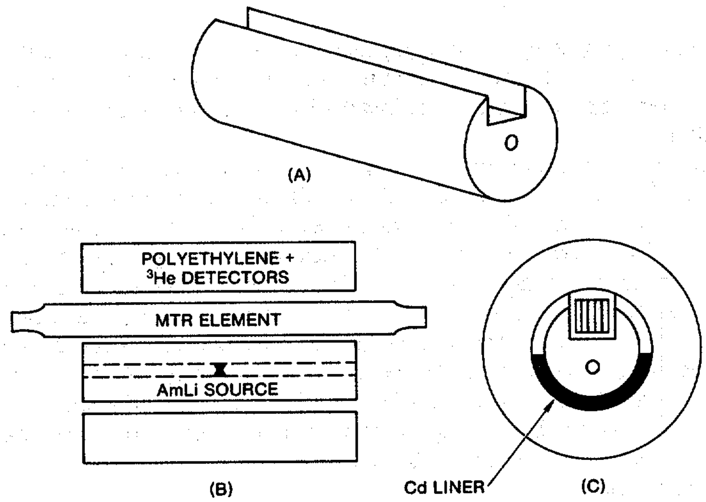

***Fig. 17.26** Horizontal configuration of the AWCC with a polyethylene insert used for the assay of materials-testing-reactor (MTR) fuel plates and elements.*

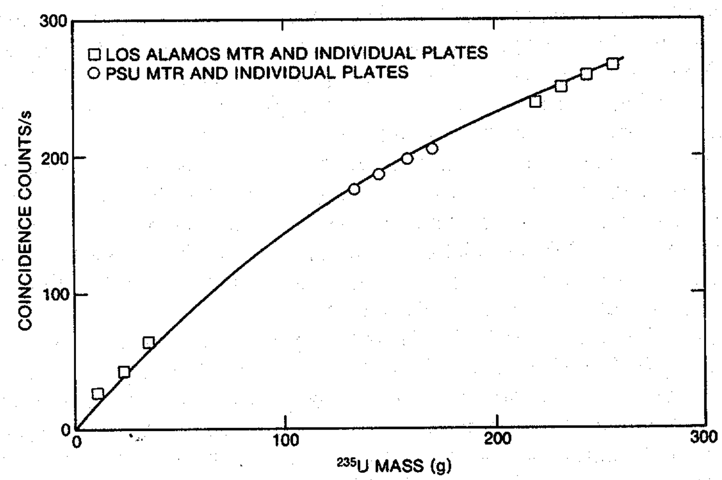

***Fig. 17.27** Calibration curve for MTR fuel plates and elements measured in the AWCC.*

17.3.2 The Uranium Neutron Coincidence Collar (UNCC)

For safeguards purposes, it is of high interest to measure full fuel assemblies because they constitute the output product from the plant and the input to the reactors. Enriched uranium is often transferred from one installation or country to another in the form of fuel assemblies.

An active neutron interrogation technique (Ref. 22) has been developed for measurement of the ^{235}U content in fresh fuel assemblies. The method employs an AmLi neutron source to induce fission reactions in the fuel assembly and coincidence counting of the resulting fission reaction neutrons. Coincidence counting eliminates the undesired neutron counts from the random AmLi interrogation source and room background. When no interrogation source is present, the passive neutron coincidence rate gives a measure of the ^{238}U through the spontaneous fission reactions. When the interrogation source is added, the increase in the coincidence rate gives a measure of ^{235}U. The Uranium Neutron Coincidence Collar (UNCC) system can be applied to the fissile content determination in boiling-water-reactor (BWR), pressurized-water-reactor (PWR), and other type fuel assemblies for accountability, criticality control, and safeguards purposes.

Active neutron systems using thermal neutron interrogation, such as the UNCC, have neutron self-shielding problems that limit the sensitivity in the interior of an assembly, but the present UNCC compensates for this limitation by fast-neutron multiplication, which is higher in the central region. The multiplication effect is enhanced by the coincidence counting because of the increase in the effective number of time-correlated neutrons emitted by the sample when multiplication occurs. In effect, the system works like a reactivity gage for the fuel assembly, and the removal of fissile material from the assembly lowers the neutron reactivity and thus the coincidence response.

The UNCC consists of three banks of ^{3}He tubes and an AmLi source embedded in a high-density polyethylene body with no cadmium liners. The 18 ^{3}He neutron detector tubes are 2.54 cm in diameter and 33 cm long (active length). The polyethylene body performs three basic functions in the system: (1) general mechanical support, (2) interrogation source neutron moderation, and (3) slowing down of induced fission neutrons prior to their detection in the ^{3}He tubes. For inspection applications, it is desirable to make the system portable. The weight of the detector system is $\sim$30 kg.

The complete assay system shown in Figure 17.28 consists of the detector body, the electronics unit, the HP-97 calculator, and a support cart. For applications, the cart is moved next to a fuel assembly. The back detector bank of the unit is hinged to aid in positioning the system around the fuel assembly.

Tests and evaluations of the UNCC have been performed at both PWR (Ref. 23) and BWR (Ref. 24) fuel fabrication facilities. Active-mode interrogation to measure ^{235}U content and passive-mode coincidence counting to determine ^{238}U content were both carried out. The UNCC measures the ^{235}U or ^{238}U content per unit length, which is proportional to the enrichment for a given type of assembly. The sample region is $\sim$400 mm long, centered in the midplane of the detector body.

A series of measurements were performed (Ref. 23) using full-size (17- by 17-rod) PWR assemblies with enrichments ranging from 1.8 to 3.4% ^{235}U. The thermal-neutron interrogation was saturated for all of the fuel assemblies; however, the measured response continued to increase as a function of enrichment because the fast-neutron

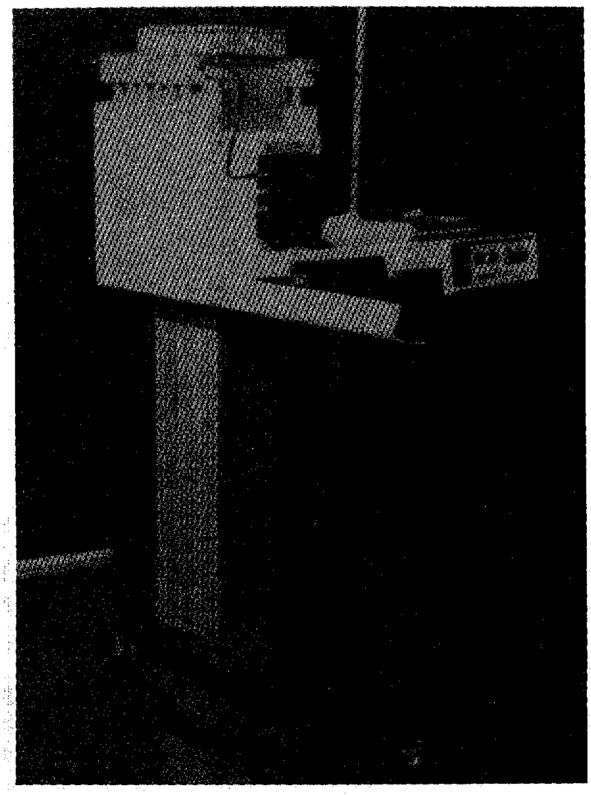

Fig. 17.28 Uranium Neutron Coincidence Collar (UNCC) with the standard coincidence electronics package in position for the measurement of a mock PWR fuel assembly.

multiplication increased with increasing enrichment. Similar measurements were performed for BWR fuel, and the calibration curve in Figure 17.29 corresponds to 8- by 8-rod BWR fuel assemblies.

In summary, the statistical precision for a 1000-s run varied from 0.6 to 0.9% (1σ), depending on the type of assembly. For longer counting periods, the ultimate precision was about 0.1% for repeat runs with a fixed geometry. The response curve was not saturated and continued to increase as the enrichment increased through the normal range of LWR fuel. Relative loading variations as small as 1.9% can be detected in a measurement time of 1000 s. Longer measurements can further reduce the statistical uncertainties. The UNCC has recently been put into routine use for inspection applications.

17.3.3 The Passive Neutron Coincidence Collar (PNCC)

The UNCC just described has been modified for verification of mixed-oxide fuel contained in FBR subassemblies or LWR assemblies (Ref. 25). Mixed-oxide fuel assemblies have a strong internal neutron source from the spontaneous fission of ^{240}Pu and from (α,n) reactions, so it is not necessary to use an external AmLi neutron source to

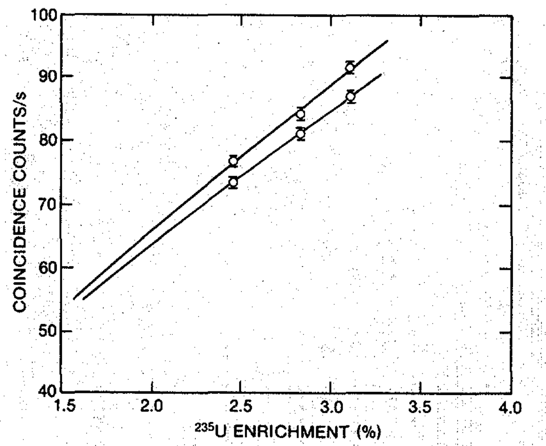

Fig. 17.29 *Calibration curves for the UNCC applied to 8- by 8-rod BWR fuel assemblies with different gadolinium loadings.*

induce fissions. The Passive Neutron Coincidence Collar (PNCC) (Figure 17.30) is similar to the UNCC except that the side containing the AmLi neutron source has been replaced by a fourth detector bank and removable cadmium liners have been placed between the detector and the fuel assembly. The PNCC has been designed with the same basic dimensions and specifications as the standard UNCC for interchangeability of parts.

In the passive mode, the neutrons originating from spontaneous fission reactions are measured using normal neutron coincidence counting to determine the ^{240}Pu-effective. In the active mode, the passive neutrons are reflected back into the assembly to induce fission reactions in the fissile component of the fuel. To determine the fraction of the neutrons resulting from the reflection process, the albedo of the boundary surrounding the assembly is changed by inserting and removing a cadmium liner.

Both the coincidence rate (R) and totals rate (T) are measured with and without the cadmium absorber. The normal passive-mode calibration curve corresponds to R vs ^{240}Pu-effective, and it is generally necessary to make corrections for the multiplication from the fissile component. Various techniques have been used to make this correction, and the present cadmium ratio determination gives a measure of the fissile component and multiplication.

The induced fission rate from the reflected neutrons is proportional to the quantity R (without cadmium) $-$ R (with cadmium) $= \Delta R$. However, ΔR is also proportional to the neutron source strength, which is different for each subassembly. To remove the source strength from the response function, one divides by T to obtain the quantity $\Delta R/T$, which is related to the fissile content independent of the source strength.

Preliminary measurements with FBR subassemblies have been carried out at the Windscale Works in the United Kingdom (Ref. 26). Both the passive and active modes were evaluated. Figure 17.31 shows the results of the measurements; the lower curve corresponds to the normal ^{240}Pu-effective results with the cadmium liners in place and the upper curve shows the increase in response when the liners are removed. This increase is caused by the additional fissions from the self-interrogation of thermal

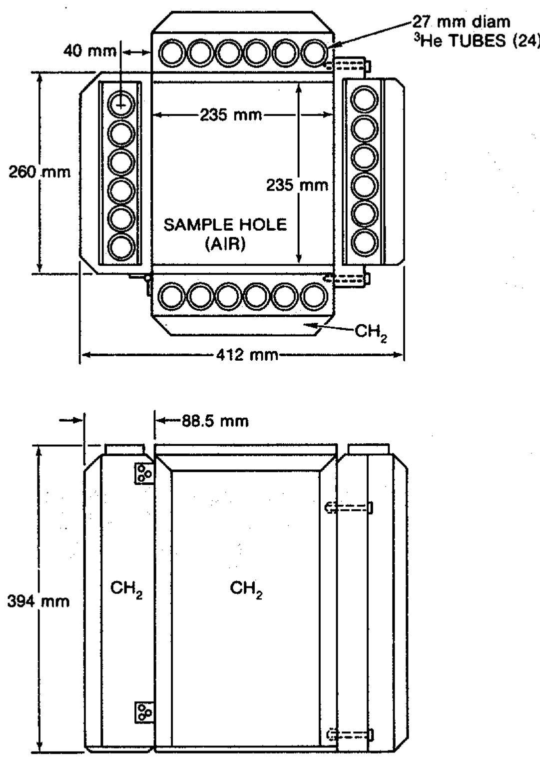

***Fig. 17.30** Schematic diagram of the Passive Neutron Coincidence Collar (PNCC) used for the passive/active assay of mixed-oxide fuel assemblies.*

neutrons. If there were no fissile material present, there would be no separation in the curves. The results of the tests gave a standard deviation of 0.75% for the passive measurement and 3 to 7% for the active measurement for a 1000-s counting time. The unit will be used in the future for verifying the plutonium content of fresh fuel assemblies.

17.3.4 Receipts Assay Monitor (RAM) for UF_6 Cylinders

In order to safeguard and account for the highly enriched uranium produced by enrichment plants, it is necessary to measure the ^{235}U content of UF_6 product storage cylinders. For enrichments above 20% ^{235}U, the UF_6 is stored in Model 5A cylinders that are nominally 127 mm in diameter and 914 mm tall. Current methods of measuring enrichment of this material include counting the 186-keV gamma-ray emissions from ^{235}U near the surface of the cylinder. A new neutron assay technique has been developed (Ref. 27) that directly samples the entire UF_6 volume of Model 5A storage cylinders to determine ^{235}U content. This passive technique, based on self-interrogation and coincidence counting, was identified after evaluating a variety of possible applications of the Neutron Coincidence Collar. The coincidence counter that was developed to implement this technique is the RAM illustrated in Figure 17.32.

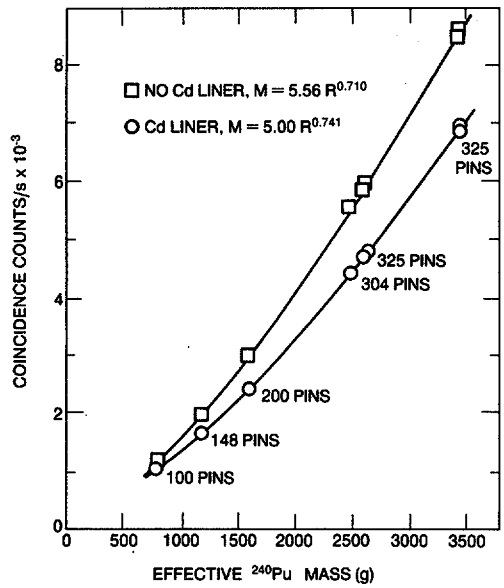

***Fig. 17.31** Results of passive assay of FBR fuel subassemblies with different pin loadings using the PNCC.*

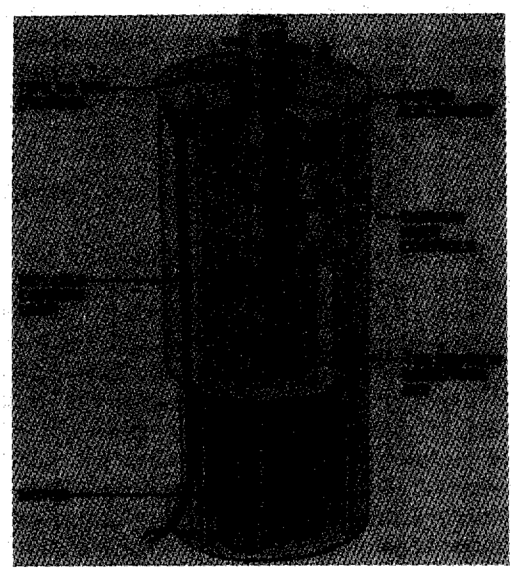

***Fig. 17.32** Receipts Assay Monitor (RAM) used to verify the ^{235}U content of Model 5A UF_6 cylinders.*

The RAM (Ref. 27) contains 20 ^{3}He tubes of 61-cm active length. Cadmium sleeves on the ^{3}He tubes are used to obtain a flat efficiency profile over the UF_6 fill height, which is typically 30 to 40 cm. Fast AMPTEK electronics are built into the top of the counter, and some shock absorbing materials are provided in this region to minimize possible impacts from UF_6 cylinders as they are lowered into the well. A unique feature of the RAM is the motor-driven cadmium liner, which can be operated manually or by an external microcomputer. A typical assay sequence consists of a 120-s measurement with the liner down and a 360-s measurement with the liner up, yielding a counting precision of about 0.5%.

In this new passive/active coincidence technique, passive neutrons from (α,n) reactions in the UF_6 are utilized to induce fission reactions (active) in the ^{235}U. Because the (α,n) neutrons are emitted randomly in time, the coincidence counting rate R gives a direct measure of the induced fission rate. The (α,n) "interrogation source strength" is measured by the totals counting rate T. The ratio R/T is proportional to $M(M - 1)$, where M is the net leakage multiplication, and is independent of the (α,n) source strength. The quantity $M(M - 1)$ is, in turn, closely related to ^{235}U content.

The primary source of (α,n) neutrons in enriched UF_6 is the alpha decay of ^{234}U reacting with fluorine atoms (see Table 11-3 in Chapter 11). In addition, ^{232}U can contribute a small fraction of the alpha particles. There is also a source of time-correlated neutrons from the spontaneous fission of ^{238}U. This rate is low (1.36×10^{-2} n/s-g ^{238}U) and is negligible for the higher enrichments because of the decrease in ^{238}U and the increase in ^{234}U. The magnitude of the ^{238}U spontaneous fission contribution is about 10% of the induced ^{235}U signal for an enrichment of 20% ^{235}U; it is less than 1% for enrichments greater than 50% ^{235}U (see Tables 14-3 and 14-4 of Chapter 14).

Figure 17.33 shows assay results for 38 Model 5A UF_6 cylinders measured by self-interrogation (Ref. 27). The coincidence-to-totals ratio R/T was corrected by a factor

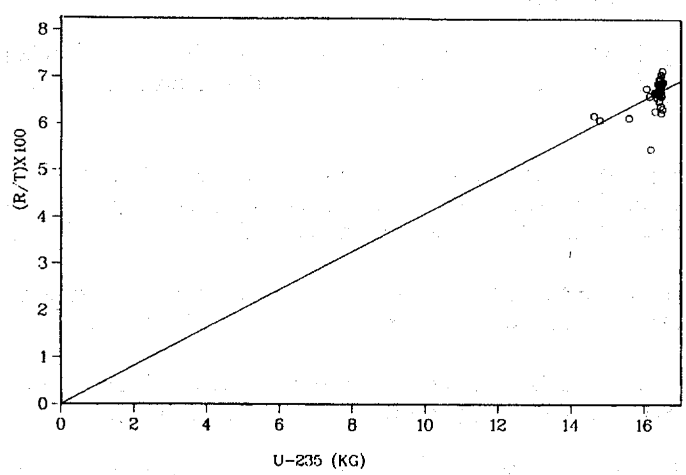

***Fig. 17.33** Assay results for 38 Model 5A UF_6 cylinders measured with the RAM. The passive, corrected R/T ratio is plotted as a function of ^{235}U content.*

based on the increase in the totals rate that occurs when the cadmium liner is removed. This correction factor helps compensate for variations in UF_6 density and self-multiplication from one cylinder to the next. The observed scatter about the fitted curve is about 10% (1σ) without the correction and 2.8% with the correction. This scatter is expected to decrease as the correction based on the movable cadmium liner becomes better understood. Data for many partially-filled cylinders is not shown in Figure 17.33, but the corrected R/T ratio is expected to provide a nearly linear calibration curve, and should be able to verify the ^{235}U content over a wide range of fill heights.

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